CONDUCTANCE QUANTIZATION IN GOLD NANOWIRES AT LOW TEMPERATURE

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When a scanning tunnelling microscope (STM) tip is driven into a metallic sample surface a nanometer sized wire (nanowire) is formed during the subsequent retraction. The electrical conduction measured during this retraction process shows signs of quantized conductance in units of $2e^2/h$. Due to the inherent non-reproducibility of the measured conductance curves a standard technique is to build histograms from a large number of curves. Such histograms, built with conductance experiments on gold nanowires at room temperature, show 3-4 peaks at integer values of $2e^2/h$, while in a low temperature mechanically controlled break junction study only the first peak is reported. In this work, histograms made up of thousands of consecutive curves at 4K are presented, showing up to 5 conductance peaks. An explanation for this discrepancy could be a higher nanowire temperature resulting from the higher retraction speed used in our measurements. However, a simple estimation, where we used macroscopic heat transport theory, resulted in a very low temperature increase, less than 1 μK, ruling out this possibility. Thus, no significant difference with previous room temperature studies were observed, pointing to a conductance quantization that is the same at room and low temperature.

1. Introduction

The electrical conductance through a narrow constriction with a diameter of the order of the electron wavelength is quantized in units of $G_0 = 2e^2/h$ [1,2]. Such conductance quantization is observed in semiconductor devices containing a two-dimensional electron gas (2DEG) at low temperature [3,4]. Similar effects are possible [5,6] at room temperature in metallic wires with a diameter of the order of 1 nm (nanowires) and are observed using scanning tunnelling microscopy (STM) [7-11], mechanically controlled break junctions (MCBJ) [12-15], or as recently shown [16,17] just by using plain household wires. These techniques use the same basic principle: by pressing two metal pieces together a metallic contact is formed which can be stretched to a nanowire by the subsequent separation of the electrodes (see inset in Fig. 1). The conductance in such a system is found to decrease in abrupt steps, of about $2e^2/h$ height, just before the contact breaks. Due to the inherent non-reproducibility of the measured conductance curves, histograms are constructed using a few hundred experimental curves [18]. The scientific relevance of these histograms has been the subject of a recent controversy [18,19]. One interpretation of the stepped behaviour of the conductance is based on conductance quantization. The other view describes the conductance steps as due to the discrete atomic size which gives rise to discrete contact size changes during the nanowire elongation process.

In an MCBJ study by Krans [15] on Au nanowires at 4.2 K no signs of conductance quantization are observed apart from a well-defined conductance peak at 1 G_0, while at 77 K three conductance peaks are seen. In another MCBJ study, Muller *et al*. [14] show that, at room temperature, conductance quantization is clearly seen and more prominently than in the earlier low temperature measurements. This is in agreement with all STM-experiments on gold at room temperature [7-11]. The explanation [14,15] for this temperature dependency in the MCBJ experiments is that for higher temperature, due to the higher kinetic energy of the atoms, the contact can explore a wider range of structures to find the most favourable atomic configuration giving the wire a more favourable form for quantized conductance to be observed.

To some extent this is also supported by numerical simulations by Bratkovsky *et al*. [20] where the nanowire tends to become more uniform in cross-section and internal defects are seen to more easily heal at high temperatures. However, the relevance to the experiments is not clear since the pulling speed are many orders of magnitude larger in the simulations than in the experiments (3.5 ms^{-1} for simulations, 1 μms^{-1} for STM experiments, and 0.01 nms^{-1} for the MCBJ experiments). In contrast to the MCBJ experiments, in a recent STM study by Sirvent et al. [21] three clear peaks are resolved at three different temperatures: 4, 77, and 300 K, however not exactly at integer values.

In this report we show that, using an STM at 4 K, up to five peaks at integer values of G_0 could be observed. Furthermore, using a simple estimation based on macroscopic heat transport theory, the higher separation speed in STM as compared to MCBJ, will not rise the temperature significantly, which could have explained the experimental discrepancies.

2. Experimental

The tips were made of 0.25 mm 99.99 % pure gold and the samples were evaporated gold thin films. The measurements were carried out in vacuum using a low temperature STM at 4K. To build the histograms, a triangular waveform was fed to the piezo-actuator driving the tip repeatedly in and out of contact with the sample surface with a typical frequency of 5 Hz and with an amplitude of 1.4 μm, which gives a speed of 14 μm/s. During this procedure the conductance was measured using a current to voltage converter with a gain of 10^5 (1 V/100 μA, 1 μs rise time, and 3 μs settling time). A 500

MHz bandwidth and 5 G samples/s, 8-bit, digital oscilloscope (LeCroy 9345AM) was used for real time building of the histograms. The tip-sample bias in all experiments reported here was 90.3 mV corresponding to a quantum current step of 7 μA ($2e^2/h$ is about 77.5 μS). Notice that all the measured curves were used to build the histogram. Only contact breakage experiments were used to construct the histograms. The histograms presented here are smoothed by averaging 3 bins to the side to remove noise. A better way is to compensate for the non-ideal differential linearity (NIDL) [22,23]. Both approaches obtain similar results but the NIDL correction produces sharper peaks.

3. Results

Fig. 1 shows a conductance histogram built with 5000 consecutive indentations experiments using Au electrodes at 4.2 K and with an electrode separation speed of 20 μm/s. It clearly shows peaks at integer values of $2e^2/h$ up to n=5. The values of the conductance are plotted after a subtraction of a series resistance of 390 Ω. This has been a common procedure in all quantized conductance reports, and usually has been justified by the resistance of the leads, i.e., what is not the nanowire itself. As shown recently in a theoretical work, this resistance can arise also from disorder within the nanowire [24], and recent experimental results point in this direction [25]. This series resistance varies with experimental conditions, but is usually in the range 200-1000 Ω. Cleaner systems usually gives lower series resistance values. Fig. 2 shows a histogram built with 900 000 consecutive curves with a similar appearance as in Fig. 1. The separation speed was 20 μm/s and a series resistance of 390 Ω has been subtracted.

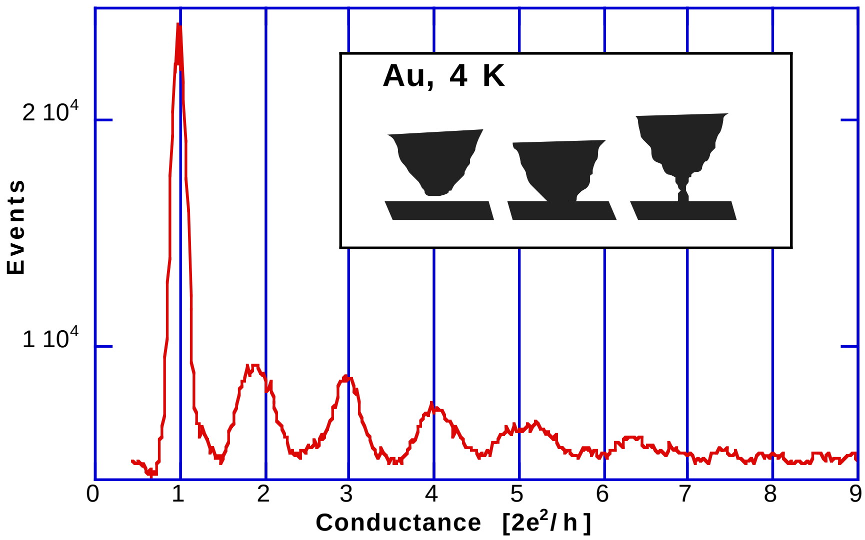

Figure 1. Conductance histogram build with 5000 consecutive curves. Inset shows the principle of nanowire formation. By pressing a tip into the sample and subsequent retracting the tip a short and narrow wire is formed.

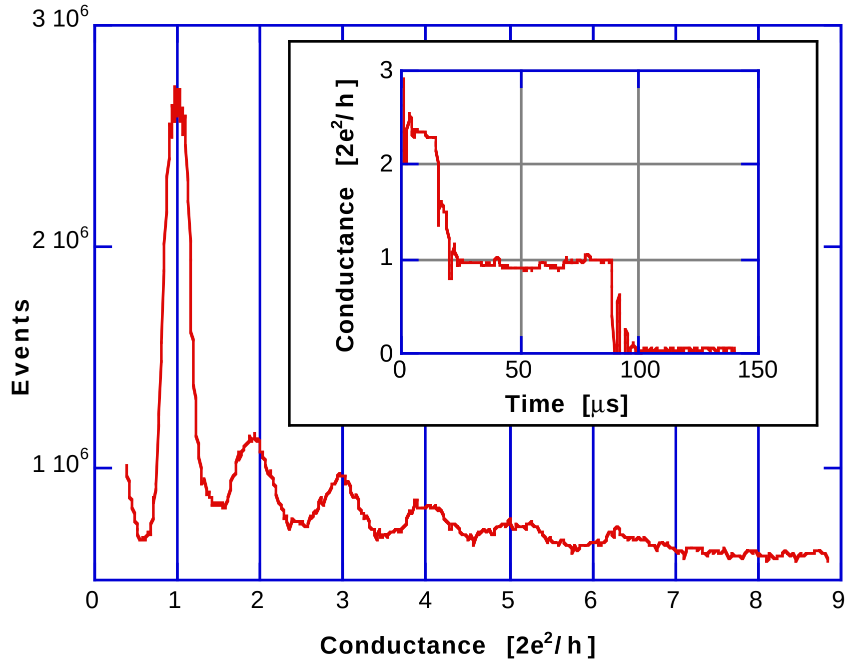

Figure 2. Conductance histogram build with 900000 consecutive curves. Inset shows a typical conductance versus time staircase.

4. Discussion

Notice in the histograms shown in Figs. 1 and 2 that, as the conductance value increases, the peak height decreases and the width increases, in agreement with room temperature STM-experiments [10,17] as well as with theoretical calculations [10]. In our RT studies [16,17] we find exactly this behaviour as well. This is in contrast with MCBJ experiments [14] at RT which show peaks with almost the same height as well as height-width relation. However, the main difference between the present results and the MCBJ results at 4K is that the MCBJ experiments does not show any sign of quantized conductance, apart from a well defined peak at *n*=1. One possible explanation for this discrepancy could be that the temperature in the wire is not the same as in the surrounding bath, due to the higher separation speed used in our STM-experiments. In the MCBJ experiments the separation speed is orders of magnitude lower than in our case (0.1 nm/s and 10000 nm/s respectively). If the energy released during the elongation process is transformed to heat, and this excessive heat is not transported away rapidly enough the temperature in the wire will be much higher than the surrounding bath. Higher temperature will give a more favourable wire, from a quantized conductance point of view, as discussed by Muller *et al*. [14] and in the theoretical work by Bratkovsky *et al*. [20]. They show that at high temperatures the nanowire tends to become more uniform in cross section and internal structure defects heal more rapidly.

A simple estimation of the temperature increase could be obtained if one consider the amount of heat that is released during the pulling of the wire. Fig. 2 inset shows a typically conductance versus time graph. The typical life time of a conductance plateau is about 100 µs. During the pulling process the cross-sectional area decreases, the surface area increases, and energy is released as the binding energies of the surface atoms are smaller than the bulk ones. If the cross-sectional area, A, of the wire is reduced by a factor of 2 the surface area will increase by a factor of 2 under constant volume conditions. If the wire is a cylinder with a diameter of 1 nm and 2 nm length, the initial surface area will change from 6.3 10^{-18} m^2 to 12.6 10^{-18} m^2. Considering a typical area of an atom of $(2\ 10^{-10})^2$ m^2, and a typical difference between binding energy in the surface and in the bulk of 1 eV per atom, a total energy of 160 eV will be released during such an elongation. If this 160 eV is released during the last plateau duration, 100 µs, the power generated will be about 0.3 pW. One may get a simple estimation of the temperature increase in the nanowire using

$$\Delta T = \dot{Q}L/A\kappa \ \ [\mathrm{K}], \qquad (1)$$

where $\dot{Q}$= 0.3 pW is the power dissipated, L is the length of the wire, and A the cross-sectional area (10^{-18} m^2). Making the assumption that the thermal conductivity, κ, is 1000 $Wm^{-1}K^{-1}$, which is typical for high purity Au at 4K, the temperature increase is less than 1 µK. Even if κ or the dissipation time are decreased orders of magnitude this estimation will still produce a very low temperature increase in the nanowire. In our rough estimate we assume that the Joule dissipation is damped in the electrode regions and not in the nanowire.

5. Conclusion

A conductance histogram with 5 clear peaks at integer values of $2e^2/h$ are observed. The height of the conductance peaks is decreasing and the width of the peaks is increasing with increasing n, much in agreement with room temperature STM-experiments [10,17] as well as with theoretical calculations [10]. It has been argued that the higher speed used in STM experiments as compared to MCBJ experiments might result in a higher temperature. However, a simple estimation, based on macroscopic heat transport, produces a temperature rise in the nanowire of the order of µK, ruling out this explanation. Therefore, conductance quantization in gold nanowires is basically the same at high and low temperatures.

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References

1. Landauer, R. (1989) Conductance determined by transmission: probes and quantised constriction resistance, *J. Phys. Condens. Matter*, **1**, 8099-8110.
2. Beenakker, C.W.J., and van Houten, H. (1991) Quantum transport in semiconductor nanostructures, *Solid State Physics*, **44**, 1-228.
3. Wharam, D.A., Thornton, T.J., Newbury, R., Pepper, M., Ahmed, H., Frost, J.E.F., Hasko, D.G., Peacock, D.C., Ritchie, D.A., and Jones, G.A.C. (1988) One-dimensional transport and the quantisation of the ballistic resistance, *J. Phys. C*, **21**, L209-L214.
4. van Wees, B.J., van Houten, H., Beenakker, C.W.J., Williamson, J.G., van der Marel, D., and Foxton, C.T. (1988) Quantized conductance of point contacts in a two-dimensional electron gas, *Phys. Rev. Lett.*, **60**, 848-850.
5. Garcia, N. (1987) *STM Workshop*, ICTP Trieste.
6. Garcia, N., and Escapa, L. (1989) Is the observed quantized conductance on small contacts due to coherent ballistic transport?, *Appl. Phys. Lett.*, **54**, 1418.
7. Pascual, J.I., Mendez, J., Gómez-Herrero, J., Baro, A.M., Garcia, N., and Binh, V.T. (1993) Quantum Contact in Gold Nanostructures by Scanning-Tunneling-Microscopy, *Phys. Rev. Lett.*, **71**, 1852-1855.
8. Olesen, L., Lægsgaard, E., Stensgaard, I., Besenbacher, F., Schiøtz, J., Stoltze, P., Jacobsen, K.W., and Nørskov, J.K. (1994) Quantized Conductance in an Atom-Sized Point-Contact, *Phys. Rev. Lett.*, **72**, 2251.
9. Pascual, J.I., Mendez, J., Gómez-Herrero, J., Baro, A.M., Garcia, N., Landman, U., Luedtke, W.D., Bogachek, E.N., and Cheng, H.P. (1995) Properties of Metallic Nanowires - From Conductance Quantization to Localization, *Science*, **267**, 1793-1795.
10. Brandbyge, M., Schiøtz, J., Sørensen, M.R., Stoltze, P., Jacobsen, K.W., Nørskov, J.K., Olesen, L., Lægsgaard, E., Stensgaard, I., and Besenbacher, F. (1995) Quantized conductance in atom-sized wires between two metals, *Phys. Rev. B*, **52**, 8499-8514.
11. Agrait, N., Rodrigo, J.G., and Vieira, S. (1993) Conductance Steps and Quantization in Atomic-Size Contacts, *Phys. Rev. B*, **47**, 12345-12348.
12. Muller, C.J., van Ruitenbeek, J.M., and de Jongh, L.J. (1992) Conductance and Supercurrent Discontinuities in Atomic-Scale Metallic Constrictions of Variable Width, *Phys. Rev. Lett.*, **69**, 140-143.
13. Krans, J.M., van Ruitenbeek, J.M., Fisun, V.V., Yanson, I.K., and de Jongh, L.J. (1995) The Signature of Conductance Quantization in Metallic Point Contacts, *Nature*, **375**, 767-769.
14. Muller, C.J., Krans, J.M., Todorov, T.N., and Reed, M.A. (1996) Quantization effects in the conductance of metallic contacts at room temperature, *Phys. Rev. B*, **53**, 1022-1025.
15. Krans, J.M. (1996) *Size Effects in Atomic-Scale Point Contacts*. Ph.D. Thesis, Rijksuniversiteit Leiden.
16. Costa-Krämer, J.L., Garcia, N., Garcia-Mochales, P., and Serena, P.A. (1995) Nanowire formation in macroscopic metallic contacts: quantum mechanical conductance tapping a table top, *Surf. Sci. Lett*, **342**, L1144-L1149.
17. Garcia, N., and Costa-Krämer, J.L. (1996) Quatum-Level Phenomena in Nanowires, *Europhysics News*, **27**, 89-91.
18. Olesen, L., Lægsgaard, E., Stensgaard, I., Besenbacher, F., Schiøtz, J., Stoltze, P., Jacobsen, K.W., and Nørskov, J.K. (1995) Quantized Conductance in an Atom-Sized Point-Contact - Reply, *Phys. Rev. Lett.*, **74**, 2147-2147.
19. Krans, J.M., Muller, C.J., van der Post, N., Postma, F.R., Sutton, A.P., Todorov, T.N., and van Ruitenbeek, J.M. (1995) Quantized Conductance in an Atom-Sized Point-Contact - Comment, *Phys. Rev. Lett.*, **74**, 2146-2146.
20. Bratkovsky, A.M., Sutton, A.P., and Todorov, T.N. (1995) Conditions for Conductance Quantization in Realistic Models of Atomic-Scale Metallic Contacts, *Phys. Rev. B*, **52**, 5036-5051.
21. Sirvent, C., Rodrigo, J.G., Agrait, N., and Vieira, S. (1996) STM study of the atomic contact between metallic electrodes, *Physica B*, **218**, 238-241.
22. Besenbacher, F., Olesen, L., Hansen, K., Lægsgaard, E., and Stensgaard, I. (1996). Experimental studies of tip-surface interactions. In *NATO Advanced Research Workshop on Nanowires*, Miraflores de la Sierra: September 23-27.
23. Costa-Krämer, J.L., Garcia, N., and Olin, H. (1996) Conductance quantization histograms of gold nanowires at 4 K, submitted for publication.
24. Garcia-Mochales, P., Serena, P.A., Garcia, N., and Costa-Krämer, J.L. (1996) Conductance in disordered nanowires: Forward and backscattering, *Phys. Rev. B*, **53**, 10268-10280.
25. Costa-Krämer, J.L., and Garcia, N. (1996) On Conductance Quantization in magnetic and non-magnetic metallic nanowires, submitted for publication.